Seismic Control of Steel Structures with Shape Memory Alloys

S.M.R. Mortazavi[1], M. Ghassemieh*[2], and S. A. Motahari[2]

[1] Shahid Rajaee Teacher Training University, Tehran, Iran
[2] School of Civil Engineering, University of Tehran, Tehran, Iran

mortazavi@srttu.edu, *mghassem@ut.ac.ir, ardavan_motahari@yahoo.com

Abstract

Shape Memory Alloys (SMA's) are able to reach very large recoverable strains. They have found their means into many inventive applications including seismic structural control. Due to their recentering capability as well as damping capacity, SMA materials are favorable for use in earthquake applications. The main idea of this research is the simultaneous use of SMA elements in different phases and steel elements is structural systems, in order to utilize each favorable characteristics. Damping capacity of Martensite phase of the SMA will leave residual strains in structure which is in contrast with the recentering characteristic of Austenite phase of the SMA. Therefore an attentive arrangement will be required in order to get the best structural performance. In this article an initiative was taken for arranging different states of SMA materials in structures as bracing elements in order to reach the best feasible performance.

Keywords

Seismic; Shape Memory Alloy; Damping; Steel Structure; Recentering

Introduction

Structural Protective Systems can be generally divided into three classes of passive energy dissipation, active or semi-active control systems and base isolation system [Soong and Dargush (1997)]. Passive devices reduce earthquake damages to structures in the course of reducing the structure demand by dissipating the input energy of the excitation and let the real structure members to withstand less severe actions. Today several types of passive energy dissipation devices has been implemented and used. However the increasing demand for better and more reliable performances requires the development of new devices with better behaviours and fewer limitations. Some of the limitations involved with current passive devices are maintenance for fluid viscous dampers, durability for rubber-based devices and complexity of installation and the need for replacement after severe earthquakes for those based on steel yielding or lead extrusion and dependence upon temperature for polymer based devices [Dolce and Marnetto (2000)]. One alternative of using current passive energy dissipation devices are Shape Memory Alloyed based components.

Shape memory alloys, one of the new and smart materials, nowadays have shown to be an interesting material for use in seismic applications because of their peculiar properties. Although Soong and Dargush (1997) have placed Smart Materials in the category of semi-active devices, Shape Memory Alloys or SMAs have been mostly regarded as passive devices in the literature [Dolce and Marnetto (2000) and Aiken, Nims, Whittaker and Kelly (1993)]. Shape Memory Alloys (mostly used as NiTi) are capable of undergoing large strains up to 8% without any residual strain, while dissipating considerable amounts of energy. This feature named superelasticity (or pseudoelasticity) besides their very high fatigue and corrosion resistance are features which are of great interest for seismic applications. The first work in the application of SMAs in seismic application goes back to the work of Graesser and Cozzarelli (1991) who evaluated the use of NiTi SMAs as seismic dampers. They studied the effect of loading frequency and history on the energy dissipation characteristics of NiTi wires.

There have been many experimental works on the applicability of SMA based devices in structures [DesRoches, McCormic and Delemont (2004), Dolce and Cardone, (2001a), Dolce and Cardone (2001b), and Dolce, Cardone, and Marnetto (2000)]; but the analytical studies using SMA devices in a modeled structure are very limited [Baratta and Corbi (2002), Bruno and Valente (2002), DesRoches and Delemont (2002), DesRoches, Leon Hess and Ocel (2000), DesRoches and Smith (2004), and Wilde, Gardoni and Fujino (2000)]. Bratta and Corbi (2002) investigated the

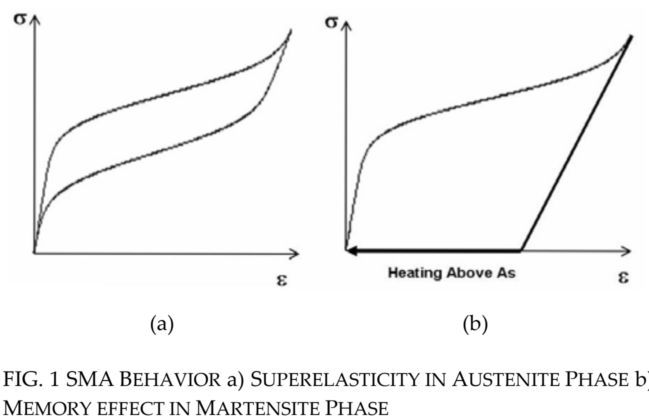
influence of SMA tendons elements as diagonal elements of a simple portal. Bruno and Valente (2002) performed a comparative investigation of traditional earthquake resisting members with SMA based resisting members. The results of this study showed that the SMA isolation system can reduce the structure response much more than any other device. DesRoches and Delemont (2002), DesRoches, Leon Hess and Ocel (2000), and finally DesRoches and Smith (2004) showed that SMA wire restrainers can significantly reduce the relative displacements of bridge piers specially in near field ground motions. Wilde, Gardoni and Fujino (2000) proposed a smart isolation system which combines a laminated rubber bearing with a device made of SMA bars.

Black, Aiken and Krumme (2006) conducted tests on large-diameter SMAs. Using steel and SMA fasteners, Abolmaali, Treadway and Aswath (2006) compared the energy dissipation of bolted T-stub connections. Czaderski, Hahnebach and Motavalli (2006) conducted experiments on a reinforced concrete beam equipped with SMA material and compared it with conventional beam. Also, Li, Li and Zhang (2007) experimentally studied the behavior of concrete beams with SMA reinforcements. Rahman, Akanda and Hossain (2008) numerically investigated the effect of cross-sectional geometry on the bending of a beam and also buckling of a column made of SMA. Motahari and Ghassemieh (2006) developed a multilinear constitutive model to capture the behaviors of SMA. Motahari, Ghassemieh and Abolmaali (2007) also introduced a special SMA damper to have both recentering and energy dissipating characteristics simultaneously. In recent studies on SMA materials, Ozbulut and Hurlebaus (2011) investigated the effectiveness of SMA/rubber-based isolation systems for protecting bridges. Johnson, Padgett and Maragakis (2008) determined the effects of SMA restrainer cables on the seismic performance of multiple frame concrete box girder bridge. Kari, Ghassemieh and Abolmaali (2011), for the new design as well as retrofitting purposes, investigated the implementation of the combination of buckling restrained braces and shape memory braces in structures. Ghassemieh, Mostafazadeh and Saberdel-Sadeh (2012) and Ghassemieh, Bahaari, Ghodratian and Nojoumi (2012) implemented both pseudoelastic and shape memory effect properties of Nitinol shape memory alloy for seismic control of concrete shear wall structure. Finally Ghassemieh, Ghodratian, Bahaari and Nojoumi (2013) utilized superelastic properties of Nitinol shape memory alloy for seismic enhancement of coupled concrete shear walls.

The main idea in this paper which is the use of different states of SMAs is based on some conclusions of DesRoches, McCormic and Delemont (2004) and Dolce, Cardone and Marnetto (2000) in their experimental studies. These remarks haven't yet been used in any analytical model. Therefore, the goal of this paper is to show the applicability of this idea for use in real structural analyses. For this reason, in order to compare between different structural systems, the idea of Structural Damage indices has been implemented.

Shape Memory Alloys

SMAs have two crystallographic phases, one parent phase called Austenite with high symmetry and one product phase with lower symmetry called Martensite. Austenite phase is stable at higher temperatures and lower stresses; while Martensite is stable at lower temperatures and higher stresses. The unique behavior of these materials is due to the phase transformation between these two phases. If the ambient temperature is above Austinite finish temperature, the specimen is in Austenite phase and the large strain induced by stress can be completely recovered by removal of stress (Superelasticity) and if the Temperature is below Martensite finish temperature, it is in Martensite Phase and a large residual strain will remain on the specimen after unloading which is also recoverable by means of heating above Austinite finish temperature (Memory effect).



(a) (b)

FIG. 1 SMA BEHAVIOR a) SUPERELASTICITY IN AUSTENITE PHASE b) MEMORY EFFECT IN MARTENSITE PHASE

Design and the Inclusion of the SMA Damper

The main objective of using SMA Damper has set to

be full recentering and good energy dissipation. Additional objectives are functional simplicity, no need for maintenance, limited encumbrance and compatible costs [Dolce, Cardone and Marnetto (2000)]. According to intensive experiments conducted by DesRoches, McCormic and Delemont (2004) and Dolce, Cardone and Marnetto (2000), the best shape and stress mode of SMAs for achieving these goals are Austenite wires in tension and Martensite bars in bending. The mechanical behavior of these two phases for seismic applications can be categorized as follow:

a) Austenite wires in tension with rather low energy dissipation capacity, in range of interest for seismic applications, zero residual strain at the end of the action, and considerable fatigue resistance; b) Martensite bars in bending with good energy dissipation capacity, large residual strains after removing the external force, thermally recoverable, very high fatigue resistance and independence from temperature and on strain rate.

As noted in the previous section Austenite phase shows full recentering capability but can't dissipate large amounts of energy especially at high rate excitations. On the other hand, Martensite has a large dissipation capability while remaining residual strains on the structure. These two objectives seem to be conflicting. But with proper implementation of both states and use of prestressing, an ideal solution can be achieved [Dolce, Cardone and Marnetto (2000)]. The idealized behavior of both recentering components and dissipating components are shown in Fig. 2. The rigid stiffness at the beginning of recentering component is obtained via prestress of the Austenite wires. As noted above, Austenite wires should always be in tension state and therefore special mechanisms of studs and tubes are needed in the device [Dolce, Cardone and Marnetto (2000)].

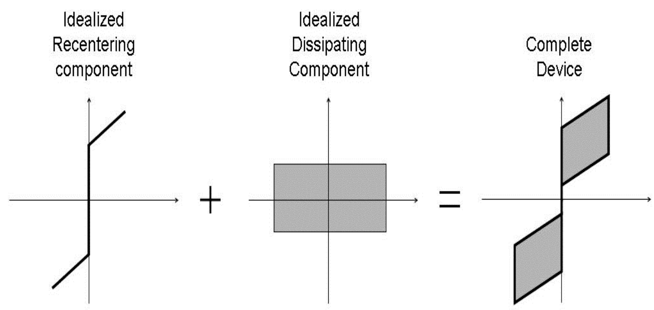
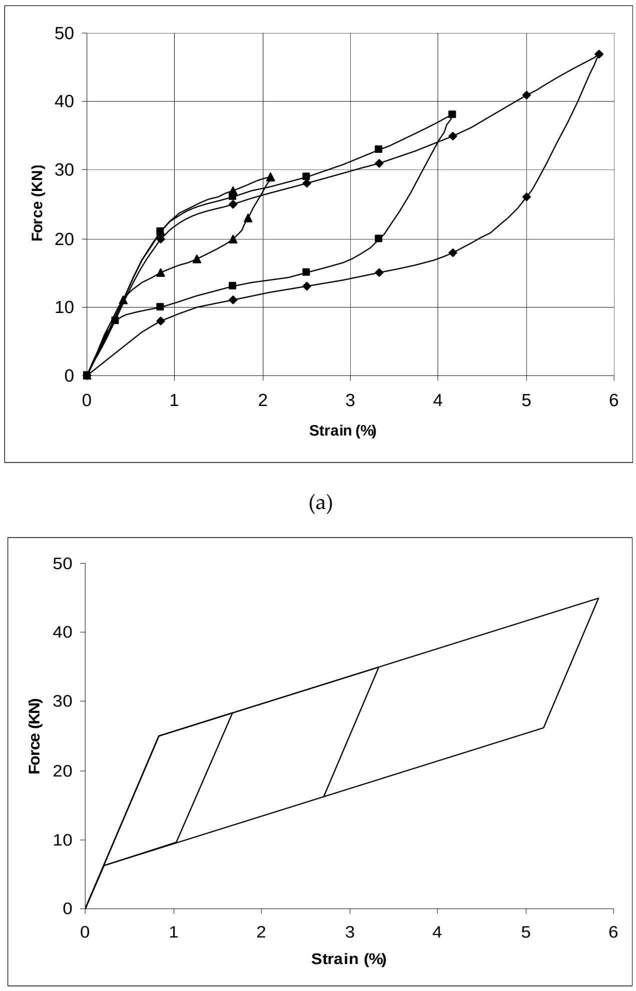


FIG. 2 RECENTERING AND DISSIPATION ENERGY COMPONENTS AND THE COMBINATION OF THE TWO

Modelling of SMA Damper (SD)

In general, constitutive modelling of shape memory materials under different loading conditions is a complicated problem and there is a large amount of literature regarding this case. Adding the complexity, limited applicability and unreliability of these models to the complexity of the introduced damper, there couldn't be any possible and rational measure to analytically model this damper. The proper and more reliable method is to use experimental results and calibrate it into the numerical model. An example of such approach can be found in DesRoches and Delemont (2002). According to Dolce, Cardone and Marnetto (2000) an approximate simplified multi-linear constitutive model for the proposed Special SMA damper is given in FIG. 3.



(a)

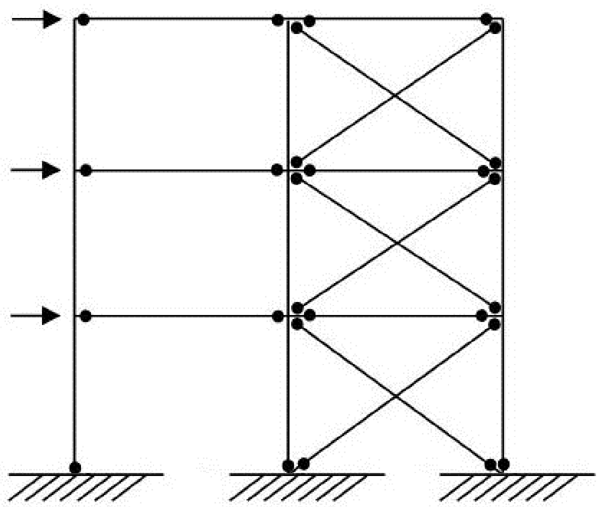
(b)

FIG. 3 FORCE – STRAIN RELATION OF SMA a) EXPERIMENTAL RESULTS [DOLCE, CARDONE AND MARNETTO (2000)] (b) MATERIAL MODEL

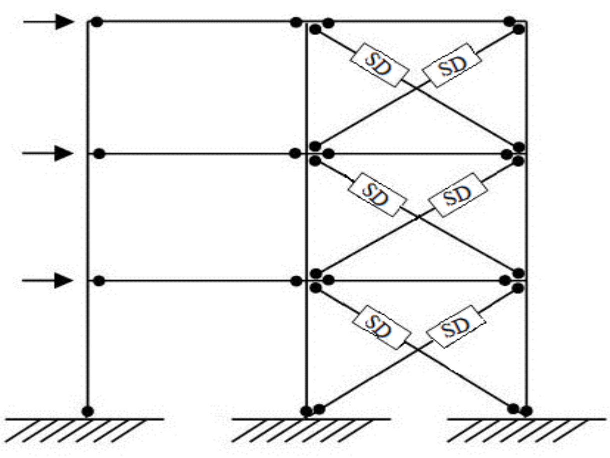
Selected Structure

For brevity, only one common three storey two bay braced steel structure, is selected for performing analyses. This Structure is shown in Fig. 4. This structure is once braced with common steel braces as shown in Fig. 4(a) and the other time with special SMA Damper as in Fig. 4(b).

The two structure systems are subjected to El Centro ground acceleration scaled to peak ground accelerations of 0.3g, 0.6g and 0.9g. Nonlinear time history analyses were performed on the two structures and the results are compared. In order to compare between the behaviours of two structures, it is important to resort to appropriate indicators of total structural damage.



(a)



(b)

FIG. 4 THREE STOREY STRUCTURES a) WITH STEEL BRACES, b) 3 WITH SPECIAL SMA DAMPER

In our Study, the damage index definition proposed by Park and Ang, and Wen (1987) which is mostly used in practice is applied. In this method, the damage of any component is derived as a linear combination of the effect of excessive deformation and a contribution due to the repeated load cycles, i.e.

$$D = \frac{u_{\max}}{u_{ultimate}} + \frac{\beta}{F_y \cdot u_{ultimate}} \int dE_h \tag{1}$$

in which u_{max} is the maximum response, β is a parameter depending on type of structural system, $u_{ultimate}$ is the ultimate limit corresponding to monotonic loading, F_y is the yield strength and dE_h is the incremental dissipated hysteretic energy. The damage of each storey is then computed as:

$$D_{storey} = \sum_{i=1}^{m} \lambda_i D_i, \quad \lambda_i = \frac{E_i}{\sum_{j=1}^{m} E_j} \tag{2}$$

where m is the number of plastic hinges of storey. The total damage of the frame is then calculated as:

$$D_{frame} = \sum_{i=1}^{n} (\lambda_i)_{storey} (D_i)_{storey}, \quad \lambda_i = \frac{(E_i)_{storey}}{\sum_{j=1}^{n} (E_j)_{storey}} \tag{3}$$

where n is the number of stories. The damage level classification as proposed by Park and Ang, and Wen (1987) is applied; as follows:

D < 0.1 (No Damage)

0.1 <D < 0.25 (Minor Damage)

0.25 < D < 0.4 (Moderate Damage)

0.4 <D < 0.1 (Severe Damage)

D >1.0 (Total Damage) (4)

The damage of SMA dampers is taken to be zero in its working limits because of its very high fatigue resistance. This character of the SMA seems to be one of the most interesting features of this material in decreasing the damage of the total building since it does not leave any damage to the structure even after long duration actions.

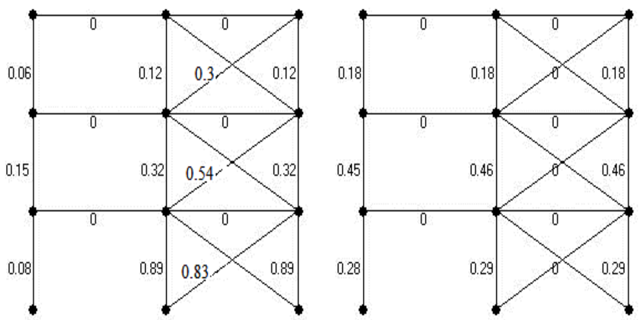
Results

The results obtained are presented in Table 1. Detailed results including each component and dissipated energies, roof displacements and element behaviors are also illustrated in Figs. 5-8 for the case of 0.9g peak ground acceleration. As shown in Table 1, the use of SMA can remarkably decrease the damage of the structure due to its special characteristics.

TABLE 1 DAMAGE INDICES FOR STRUCTURES SUBJECTED TO EL CENTRO GROUND ACCELERATIONS WITH DIFFERENT PGAS

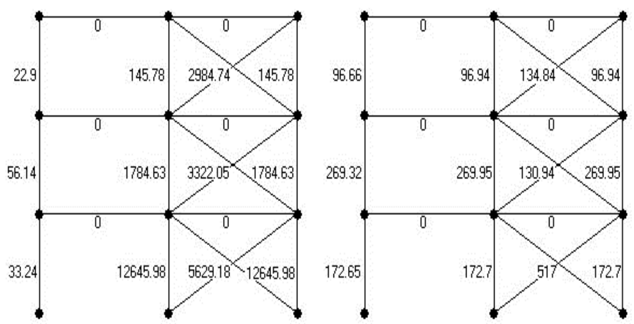
Earthquake PGA	Steel Braced System		SMA Braced System	
	D.I.	Limit of Damage	D.I.	Limit of Damage
0.3	0.27	Moderate	0.07	None
0.6	0.43	Severe	0.11	Minor
0.9	0.72	Severe	0.18	Minor

In Fig. 5, the damage indices of each individual component and of each storey are shown for both systems. In SMA system in addition to the elimination of damage of braces, the damage to the columns of the braced bay is also diminished, because the steel bracing system is stiffer (due to the low stiffness of SMA Dampers) and gains more forces and transfers the forces to the columns. At the other hand, the SMA bracing system is softer and dissipates the energy via its especial behavior instead and let the other parts of the structure to withstand less forces and actions. In Fig. 6 the dissipated energy of each element and each storey are shown in units of Kgf.Cm². As been indicated, the reason that dissipated energies are less in SMA System is that all members experience much less actions and the SMA bracing start dissipating energy at much lower force, so the magnitude of hysteretic dissipated energies are less in this system.



(a) Steel Braced System (b) SD Braced System

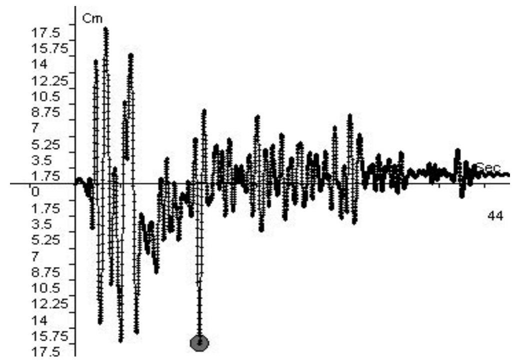
FIG. 5 COMPONENT DAMAGE INDICES FOR BOTH SYSTEMS



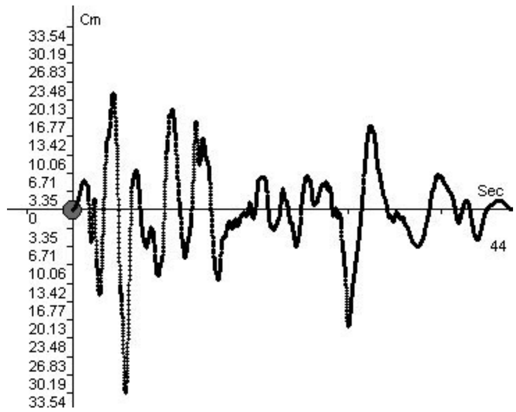
(a) Steel Braced System (b) SD Braced System

FIG. 6 DISSIPATED ENERGIES FOR BOTH SYSTEMS (UNIT: Kgf.Cm²)

In Fig. 7 the top storey displacement time histories of two systems are shown. Since the steel system is stiffer it experiences lower deformations and the damage to non-structural systems is less in steel bracing structure. This is the cost we should pay instead of getting the benefit of decreasing the structural damage in SMA bracing system. As illustrated in the figure, unlike the steel braced system, the structure is deforming in different modes with different frequencies. This is because of the rapid changes of stiffness of the SMA damper which forces the higher modes to be excited. In Fig. 8, axial force–displacement responses for 1st storey bracings are shown for two systems.

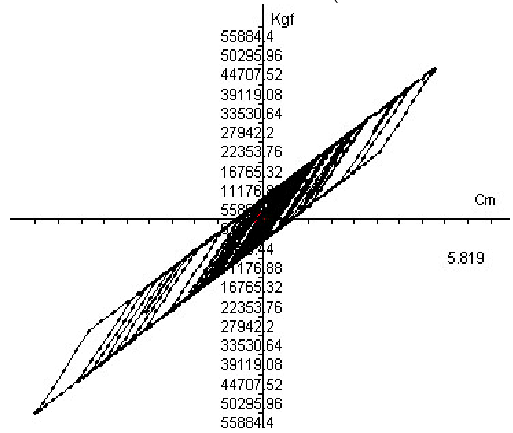


(a) Steel Braced System

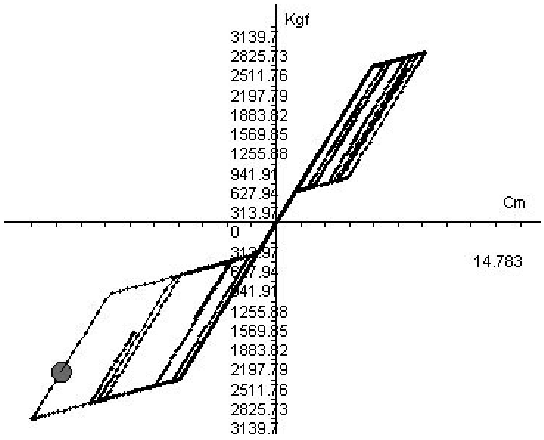


(b) SMA Braced System

FIG. 7 TIME HISTORY OF THE SYSTEM (TOP DISPLACEMENT)



(a) Steel Bracing System



(b) SMA bracing System

FIG. 8 RESPONSES OF 1ST STOREY BRACES (FORCE-DISPLACEMENT)

Conclusions

As presented in this paper, utilizing the introduced special shape memory damper the structural damage of a typical frame can be noticeably reduced. However, it is very essential to note that particular concern must be compensated in design of such a frame. The design should be proportional in a way that the SMA dampers are the main energy absorber of the system and their unique behavior is fully utilized. Furthermore, since the stiffness of the damper is much lower than the common steel braces, care should be paid also to the damage of non-structural components of the structure and keep the deformations of the structure to acceptable limits. Finally, the last thing to consider is that SMA damper changes its stiffness very rapidly and this may cause the higher modes of the structure to be excited in the event of seismic actions. Therefore it is shown that shape memory alloys can be successfully used for control of structures subjected to seismic forces due to their unique characteristics.

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